Strategic Investment in Technological Innovations

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The aim of this paper is to determine the optimal timing of technology investment of a single firm in a duopoly framework. As time passes different technologies are invented which after some time become available for the firm to adopt. The question here is not only when a firm should invest but also which technology should be adopted. For different scenarios the optimal technology investment decision is determined. Outcomes range from preemption equilibria to equilibria with second mover advantages.

Keywords: Technology investment, Strategic timing, Preemption, Second mover advantage

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1. Introduction

One of the main elements that determine economic growth nowadays is the diffusion of new technologies to firms. Research and development alone is not yet sufficient for technical progress since technological innovations yield no benefits until they are employed. In order to design policy instruments that enhance firm investments in new technologies, it is important to investigate in what circumstances firms are willing to adopt new technologies, and to identify the reasons that make the firm refrain from adoption. At the firm level it can be argued that one of the most crucial decisions is that of investing in new or improved equipment and facilities. These decisions are not only important because of the large initial capital costs involved, but also because of its impact on the firm's performance for many years into the future. Reasons for retrospection on the decision would arise if newer technologies appear soon after the purchase, or if the need for capability or adaptability to changes were not foreseen earlier when the decision was made, or they were not incorporated in the model at that time (Nair (1995)). The aim of this paper is to determine the optimal technology investment decision of an individual firm, while taking into account the possible occurrence of better technologies in the future and competition of other firms. The first paper that deals with the issue of technology investment together with competition on the output market is Reinganum (1981). She considers a duopoly with two identical firms, which both have the possibility to invest in a new technology from which the price falls over time. Despite the fact that the firms are identical, one of them is given the leader role beforehand. This implies that only this firm is allowed to invest first. The other firm is the follower which has the choice to invest at the same time as the leader or to invest later. As shown in Fudenberg and Tirole (1985) for this framework two scenarios can be identified. In one scenario the optimal outcome is joint adoption, i.e. both firms invest at the same time, while in the other scenario the follower invests later despite of the fact that the leader then obtains the largest payoff. Fudenberg and Tirole (1985) also consider the more realistic case of endogenous firm roles meaning that beforehand it is not known which firm will be the leader. In the case of dispersed adoption timings the leader earns the highest payoff so that both firms want to be the leader. This gives an incentive to try to invest earlier than its competitor, i.e. both firms will try to preempt each other. Fudenberg and Tirole show that this leads to a preemption equilibrium with dispersed adoption times and rent equalization. Stenbacka and Tombak (1994) extend this research by introducing uncertainty concerning the length of the period between the point of time that the technology is adopted and the time that it is successfully implemented. One of the shortcomings of the contributions mentioned in the previous paragraph is that only one new technology is considered, while in reality one has to deal with the occurrence of consecutive new technologies. This complicates the technology investment decision considerably, since every time the firm considers to invest in a new technology it has to take into account that there is a real probability that at a later point of time a more efficient technology will be invented[1]. The aim of this paper is to

[1] Especially information technology capital has a very high pace of technological improvement. Compared with more traditional types of capital, the efficiency of information technology capital has increased much faster over the last few decades. As an example, consider the market for personal computers. IBM introduced its Pentium PCs in the early 1990s at the same price at which it introduced its 286 PCs in the

provide a first step in analyzing this problem of when a firm should adopt a new technology knowing that a better technology will become available later, while it has to fight for a market share with an identical firm on the output market. Two technologies are considered: a current one which can be adopted now, and a new one which is more efficient and enters the input market at a known future date. Learning is incorporated in the sense that it is less costly to adopt and successfully implement the new technology if it has adopted the current technology before. As such this framework is taken from Grenadier and Weiss (1997), but in that paper the future date at which the new technology becomes available is uncertain and only one firm is considered. So, compared to Grenadier and Weiss (1997) we exchange the uncertainty for competition on the output market. In this way we are able to identify the strategic aspects of this problem. Two scenarios are worked out in detail: one where the new technology is cheap, and one where it is so expensive that it is not optimal for both firms to produce with the new technology. In the latter case we show that in a particular time interval it is optimal for one firm to invest right away in the current technology while the other firm waits with investment in order to adopt the new technology as soon as it becomes available. Which firm will do better depends on the comparison between the temporary monopoly profits gained by the first investor before the new technology arrives, versus the higher revenue the other firm obtains after the arrival date of the new technology due to the fact that it produces with a more efficient technology. In case the monopoly profits are outweighed by the higher revenue associated with the new technology, second mover

1980s. Therefore it took less than a decade for the computing technology to improve on the order of 20 times in terms of both speed and memory capacities, without increasing the cost (Yorukoglu (1998)).

advantages arise. To our knowledge, the way second mover advantages are caused here has not occurred in the literature yet[2]. These second mover advantages may lead to a better understanding of the fact that from empirical studies it could not always be concluded that early entrants perform better than later entrants. Apart from the numerous studies that found persistent market-share advantages to first entrants, there are many examples of pioneering firms that did not survive the competition of later entrants. Dutta *et al.* (1995) mention the case of EMI, which developed the first CT scanner but lost in the market place (because it lacked a technological infrastructure and marketing base in the medical field). The contents of this paper is as follows. The model is introduced in Section 2. In Section 3 the solution procedure is explained and optimal investment strategies are analyzed in detail for two specific scenarios. Section 4 concludes.

2. Model Formulation

The model is based on Grenadier and Weiss (1997), but here a duopoly with two identical firms is considered, while in Grenadier and Weiss (1997) the analysis is focussed on a single firm. To produce goods the firms need to acquire a certain technology. They can invest in a current technology which is available now. Later on, say at time T, a new and more efficient technology becomes available for adoption. In our analysis time T is assumed to be known beforehand (contrary to Grenadier and Weiss (1997) where T depends on the realization

[2] Second mover advantages are also obtained by Hendricks (1992) and Dutta *et al.* (1995). In Hendricks (1992) they are caused by ex ante uncertainty in the profitability of adoption, while in Dutta *et al.* (1995) the quality of the product improves over time.

of a Wiener process that governs the state of technological knowledge). Denote by index i the way the firm produces goods: $i = 0$ means that the firm does not produce at all, $i = 1$ says that the firm produces using the current technology, while producing with the new technology is designated by $i = 2$. The firm's profits per unit of time, while it produces with technology i and the other firm with technology j, are given by $\pi(i, j)$. Consequently, if $P(i, j)$ denotes the value of the firm while it produces with technology i and the other firm with technology j forever, it holds that

$$P(i,j) = \int_0^\infty \pi(i,j)e^{-rt}dt = \frac{\pi(i,j)}{r}, \tag{1}$$

where r is the constant discount rate. If the new technology is not available for adoption yet, i.e. $t < T$, the firm has the possibility to invest in the current technology, where the investment expenditure equals C_e. Then the firm's payoff is $P(1, j) - C_e$, where j denotes whether the other firm is producing with technology 1 or refrains from producing. From time T onwards the firm can choose to adopt the new technology. If the firm has invested in the current technology before, it must replace this technology for the new one. Then the payoff of investing in the new technology is $P(2, i) - P(1, j) - C_u$, where C_u stands for the cost of upgrading. Note that in the formulation of the payoff it is taken into account that the other firm can change its technology too at time T. If the firm adopts the new technology without having invested in the current technology before, the payoff of this investment is $P(2, i) - C_l$. Concerning the levels of the different cost parameters we impose that

$$C_u < C_l < C_e + C_u. \tag{2}$$

The first inequality in (2) denotes the learning effect in the sense that it is less costly to adopt and successfully implement the new technology if the firm already produces goods. The second inequality assures that no arbitrage is possible, i.e. it is always more costly to immediately start producing with the current technology and replacing it later by the new one, than to refrain from production initially in order to wait for the new technology to arrive. At the moment the new technology arrives the demand for the current technology will fall so that it makes sense that the acquisition cost of the current technology will fall too. This makes that if the firm did not buy the current technology before, it can become profitable to adopt this technology after time T. The payoff of this transaction is $P(1,i)-C_d$, where for C_d it holds that

$$C_d < C_e. \tag{3}$$

The worth of a particular technology falls over time, because (1) it becomes old-fashioned, (2) the firms that are most eager to buy the technology have already bought it so that technology suppliers have to drop their price in order to find additional buyers, and (3) due to learning by doing the technology supplier can produce the technology in a cheaper way. For these reasons we assume here that technology investments are irreversible. Next, we specify how the profit streams are related to each other[3]. First, it holds that when the firm produces with a given technology the highest profit it can obtain is the monopoly profit, which the firm receives if the other firm does not produce. Second, its profits will be lowest when the other firm is a strong competitor in the sense that it produces in the most efficient

[3] Note that from (1) it can be obtained that profits per unit of time $\pi(i,j)$ are related to each other in the same way as the discounted profit streams $P(i,j)$.

manner by using the modern technology. This leads to

$$P(i,0) > P(i,1) > P(i,2) \text{ for } i = 1,2. \tag{4}$$

Furthermore, by upgrading its technology, thus exchanging the current technology for the new technology, the firm gains most the less competitive the other firm is. Of course, since the new technology is more efficient, the profit stream always increases due to this exchange. Mathematically, this can be expressed as

$$P(2,0) - P(1,0) > P(2,1) - P(1,1) > P(2,2) - P(1,2) > 0. \tag{5}$$

Finally, in order to limit the number of possible cases, we focus on the scenario where for every technology investment the discounted future profit stream exceeds the immediate expenditure. Due to (2), (3) and (4) it can be concluded that this is assured by

$$P(1,2) > C_e;\ P(2,2) > C_l. \tag{6}$$

3. Solution Procedure

3.1. Candidate strategies for optimality

Since for every technology investment the discounted future profit stream exceeds the immediate cost expenditure (cf. (6)), it is optimal for the firm to invest at least once. This implies that, given that we are at a certain point of time $t < T$, each firm has four candidate strategies for optimality (cf. Grenadier and Weiss (1997)). The first strategy is called the *Compulsive strategy*. Here the firm invests right away in the current technology, and replaces this current technology by the new one as soon as the latter becomes available. The payoff of the Compulsive strategy equals[4]

$$P(1,j) - C_e + e^{-r(T-t)}\{P(2,i) - P(1,j) - C_u\}. \tag{7}$$

The second strategy is the *Buy and Hold strategy* by which is meant that the firm invests right away in the current strategy and keeps on producing with it. The firm's payoff then equals

$$P(1,j) - C_e + e^{-r(T-t)}\{P(1,i) - P(1,j)\}. \tag{8}$$

The third strategy is the *Leapfrog strategy.* Then the firm waits for the new technology to arrive and adopts it then. The payoff of this strategy is

$$e^{-r(T-t)}\{P(2,i) - C_l\}. \tag{9}$$

The fourth strategy is to wait for the new technology to arrive, and at that moment invest in the current technology, which then can be bought against a cheaper price. The payoff of this so-called *Laggard strategy* then equals

$$e^{-r(T-t)}\{P(1,i) - C_d\}. \tag{10}$$

3.2. Equilibrium strategies

The equilibrium strategies of both firms depend on the scenarios in which they have to operate. It holds that in some scenarios upgrading is optimal, implying that the payoff of

[4] In (7), as well as (8), (9) and (10), the other firm produces with technology j before time T and with technology i after time T. Of course, if j or i equals 0 it is meant that the other firm does not produce at all.

$P(2,2)-P(1,2)$	$<$	$P(2,1)-P(1,1)$	$\leq$	C_l-C_d, C_u				1
$P(2,2)-P(1,2)$	$\leq$	C_l-C_d	$<$	$P(2,1)-P(1,1)$	$\leq$	C_u		2
$P(2,2)-P(1,2)$	$\leq$	C_u	$<$	$P(2,1)-P(1,1)$	$\leq$	C_l-C_d		3
$P(2,2)-P(1,2)$	$\leq$	C_l-C_d, C_u	$<$	$P(2,1)-P(1,1)$				$4,5$
C_l-C_d	$<$	$P(2,2)-P(1,2)$	$<$	$P(2,1)-P(1,1)$	$\leq$	C_u		$6,7$
C_l-C_d	$<$	$P(2,2)-P(1,2)$	$\leq$	C_u	$<$	$P(2,1)-P(1,1)$		8
C_u	$<$	$P(2,2)-P(1,2)$	$<$	$P(2,1)-P(1,1)$	$\leq$	C_l-C_d		9
C_u	$<$	$P(2,2)-P(1,2)$	$\leq$	C_l-C_d	$<$	$P(2,1)-P(1,1)$		10
C_l-C_d, C_u	$<$	$P(2,2)-P(1,2)$	$<$	$P(2,1)-P(1,1)$				11

Table 1. Possible scenarios and their resulting solutions which are numbered in the last column.

the Compulsive strategy exceeds the payoff of the Buy and Hold strategy, while in other ones it is not. Another factor that distinguishes the different scenarios are the payoffs of the Leapfrog and the Laggard strategies: the Leapfrog payoff can exceed the Laggard payoff but it can be the other way round too. Here it also has to be taken into account that the ranking of the payoffs depends on what the other firm is doing: producing with the current technology or with the new one. In this way we arrive at Table 1 where the different scenarios are listed. Note that in Table 1 it is taken into account that when the firm exchanges the current technology for the new technology, it gains more when the other firm produces with the current technology instead of the new technology (cf. (5)). From Table 1 it can be derived that solving the model leads to eleven different solutions, which are numbered in the last column. In the next subsections we describe two of these solutions in detail. In both subsections we start out by analyzing the case of *exogenous firm roles*, i.e., despite the fact that both firms are identical one of them is given the leader role beforehand. This implies that only this firm is allowed to invest first. The other firm is the follower, which can choose between investing at the same time as the leader resulting in joint adoption, or investing later. The resulting solution is taken as a starting point to consider the more realistic case of *endogenous firm roles*, meaning that beforehand it is not known which firm will be the leader.

3.3. Equilibrium strategies if the new technology is cheap

The solution we have in mind here is solution nr. 11 in Table 1, from which it can be obtained that solution nr. 11 is optimal when

$$P(2,1) - P(1,1) > P(2,2) - P(1,2) > \max(C_u, C_l - C_d). \tag{11}$$

Due to (7) and (8) we can conclude that under (11) Compulsive dominates Buy and Hold, while (9) and (10) imply that Leapfrog dominates Laggard.

3.3.1. Exogenous firm roles

Despite of the fact that both firms are identical one of them gets the leader role beforehand so that the other firm is the follower. Straightforward calculations lead to the equilibrium strategies that are presented in Figure 1. This figure should be read as a feedback diagram. By this it is meant that the figure shows which policy both firms should choose at a particular point of time. In Figure 1 four time intervals can be distinguished. Concerning the notation, $t_{xy,z}$ means that at this point of time a firm is indifferent between strategy x and y, given that the other firm performs strategy z. Here the names of the strategies are abbreviated (C: Compulsive, Le: Leapfrog, La: Laggard, and B: Buy and Hold). So, if for instance the game starts at a point of time $t \in [t_{CLe,Le}, T)$, according to Figure 1 both firms should follow a Leapfrog strategy. Since in this scenario the new technology is attractive, only those

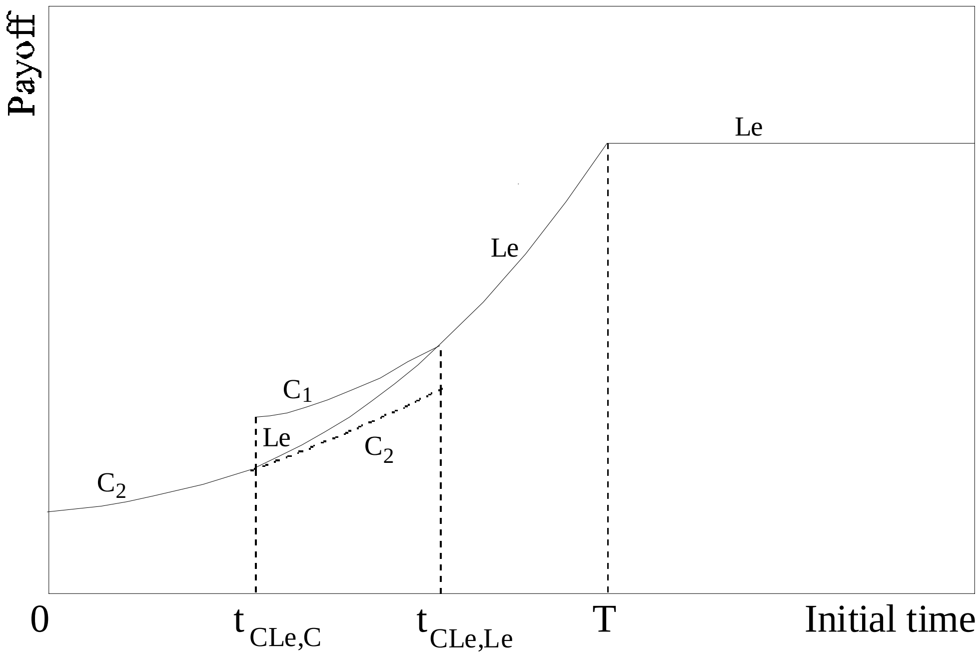

Figure 1. Relevant strategies with their payoffs as function of the initial time of the game, under scenario (11). C_1 is the Compulsive payoff if the other firm applies Leapfrog, C_2 is the Compulsive payoff in case both firm apply the Compulsive strategy and Le is the Leapfrog payoff if the other firm applies the Compulsive strategy.

strategies occur under which this technology will be bought: Compulsive and Leapfrog. When the point of time at which the new technology appears on the market lies relatively far in the future, it is optimal for both firms to apply the Compulsive strategy, i.e. buy the current technology immediately and upgrade at time T. This explains why in Figure 1 for both firms the Compulsive strategy is optimal on the time interval $[0, t_{CLe,C})$. On the time interval $[t_{CLe,C}, t_{CLe,Le})$ T is not that far away, which implies that, given that the leader announces a Compulsive strategy, the follower will prefer Leapfrog, i.e. refrain from immediate investment in order to wait for the new technology to arrive. The explanation is that the time interval in which the current technology will be used is too short to make investing in the current technology profitable. Also the learning effect, i.e. implementing the new technology is cheaper when the firm has already production experience due to using the current technology, cannot make up for this (cf.(2)). But, given that the follower will not adopt the current technology so that it will not produce before time T, by investing in the current technology the leader can become a monopolist until the time that the new technology arrives. This explains the upward jump of the payoff resulting from a Compulsive strategy right at $t_{CLe,C}$. On the third interval $[t_{CLe,Le}, T)$ the arrival of the new technology is that near that for both firms it is optimal to wait with investment until the new technology becomes available. This explains the occurrence of the Leapfrog strategy on this interval. On the last interval $[T, \infty)$ the firms can choose among investing right away in the current and the new technology. Due to the arrival of the new technology the price of the current technology has fallen from C_e to C_d. However, as can be derived from (9),(10), and (11), it is still more profitable to adopt the new technology so that both firms apply the Leapfrog strategy.

3.3.2. Endogenous firm roles

Since firms are identical there seems to be no reason why one of these firms should be given the leader role beforehand. This makes the outcome of the exogenous firm roles case hard to accept. In this subsubsection however, we use this outcome to generate the equilibria of the case where it is not known beforehand which firm will invest first. The fact that firms are identical also implies that it is reasonable to impose that firms behave in the same manner.

Therefore we restrict ourselves to symmetric strategies. Looking at Figure 1 we see that, apart from the interval $[t_{CLe,C}, t_{CLe,Le})$, in the case of exogenous firm roles the firms choose for the same strategy, meaning that they invest at the same time in the same technology. Hence, there is no difference in the behavior of leader and follower so that we end up with the same equilibria as in the case of endogenous firm roles. So, what is left to do is to determine the equilibria on the interval $[t_{CLe,C}, t_{CLe,Le})$. From Figure 1 we obtain that the firm that invests first gets the highest payoff resulting from the Compulsive strategy. The other firm plays Leapfrog, and this payoff is less than the Compulsive one. In case both firms invest at the same time, they both get the Compulsive payoff associated with the dotted line in Figure 1. It is clear that the Compulsive payoff of the first investor lies above this one, since the first investor is monopolist until time T. Let us determine the optimal strategy of both firms if the game begins at a point of time $t_0 \in [t_{CLe,C}, t_{CLe,Le})$. It is attractive to be the first investor, but when both firms apply the strategy "invest right away at time t_0", with probability one they end up with a compulsive payoff associated with the dotted line in Figure 1. Therefore, we have to look for a mixed strategy. To do so, let us define $V\ (t)$ as the value of the firm at time t, $p\,(t)$ is the probability that the firm invests at time t, while $q\,(t)$ is the probability that the other firm invests at time t. $p\,(t)$ and $q\,(t)$ are the control variables of both firms that need to be optimally determined. Furthermore, to distinguish between the two Compulsive payoffs, the payoff earned by the firm being the only one applying the Compulsive strategy is denoted as $C_1(t)$, whereas $C_2\,(t)$ is the payoff in case both firms play Compulsive. Then, while suppressing the time arguments, the value of the firm is given by

$$V = p\,(1-q)\,C_1 + (1-p)\,qLe + pqC_2 + (1-p)\,(1-q)\,V. \tag{12}$$

This equation reflects that with probability $p(1-q)$ the firm invests first so that it obtains the payoff C_1, with probability $(1-p)q$ the other firm invests first so that the firm gets the Leapfrog payoff, with probability pq the firms invest at the same time leading to a payoff being equal to C_2, while with probability $(1-p)(1-q)$ nothing has happened so that we are back in the original situation. Rewriting (12) gives the expression for the value of the firm at time t, where $t \in [t_{CLe,C}, t_{CLe,Le})$:

$$V = \frac{p(1-q)C_1 + (1-p)qLe + pqC_2}{1-(1-p)(1-q)}. \tag{13}$$

To find the optimal value for p we differentiate (13) w.r.t. p and put this expression equal to zero. This eventually leads to the following equality:

$$V_p = \frac{q((1-q)C_1 - Le - qC_2)}{(1-(1-p)(1-q))^2} = 0. \tag{14}$$

It is easily verified that $V_{pp} < 0$, so that satisfying (14) indeed leads to a maximum value of the firm. Since we only consider symmetrical strategies we impose that

$$p = q. \tag{15}$$

Combining (14) and (15) leads to the following optimal value for p:[5]

$$p = \frac{C_1 - Le}{C_1 - C_2}. \tag{16}$$

From Figure 1 we learn that $C_2 < Le < C_1$, so that we are sure that the probability p lies between zero and one. Fudenberg and Tirole (1985) show that the strategies formed

[5] A similar value for p was found in Fudenberg and Tirole (1985) and Simon (1987). The latter paper applied a timing game to solve a so-called gunfighter problem.

by (15) and (16) are a perfect equilibrium, while the expected value of the firm equals Le. The last result can be checked by substitution of (15) and (16) into (13). From (16) we further obtain that, given the difference $C_1 - C_2$, the firm is more eager to invest when the difference between the payoff associated with investing first and a Leapfrog payoff is large, which makes sense. In a similar way as in Simon (1987) it can be shown that

$$\int_t^{t+\varepsilon} p(s)ds = 1 \tag{17}$$

for any $\varepsilon > 0$. This can be proved by picking a very fine discrete-time grid with n grid points on the interval $[t, t+\varepsilon]$ and play p on this grid. By letting n go to infinity equation (17) follows. If we let ε approach zero we can conclude from (17) that in the game starting at time t one of the firms will surely invest right at time t. Of course, both firms do not want to invest at the same time, because it leaves them with the lowest possible payoff C_2. From (13) and (15) it can be derived that the probability of occurrence of such a "mistake" is $p/(2-p)$, which naturally increases with p[6]. Due to the fact that $C_1 > Le$, (16) learns that p is strictly positive, so that the probability of making a mistake is strictly greater than one. This is different from the model in Fudenberg and Tirole (1985), where this probability is zero due to rent equalization. In a similar way it can be obtained that the probability of a firm being the first investor equals $(1-p)/(2-p)$. Due to symmetry this is also the probability of ending up with a Leapfrog payoff. Since the probability of simultaneous adoption increases with p, it follows that the probability of being the first investor decreases with p, which is at

[6] Note that by allowing this mistake, in this respect the paper is more advanced than Dutta *et al.* (1995) and Grenadier (1996), where it was assumed beforehand that both firms cannot act at the same time.

first sight a strange result. But it is not that strange if (15) is taken into account, i.e. if one firm increases its probability to invest, the other firm does the same. This results in a higher probability of making a mistake, which leaves less room for the equal probabilities of being the first investor and playing Leapfrog. Substitution of the Compulsive and the Leapfrog payoffs, which are given by (7) and (9), into (16) results in the following expression for p on the time interval $[t_{CLe,C}, t_{CLe,Le})$:

$$p(t) = \frac{P(1,0) - C_e + e^{-r(T-t)}(P(1,0) + C_l - C_u)}{(P(1,0) - P(1,1))(1 - e^{-r(T-t)})}. \tag{18}$$

To see how p develops over time, differentiate (18) with respect to t, and eventually obtain

$$p'(t) = \frac{re^{-r(T-t)}(C_l - C_u - C_e)}{(P(1,0) - P(1,1))(1 - e^{-r(T-t)})} < 0, \tag{19}$$

where the inequality sign follows from (2). The implication is that if we consider two games, one beginning at time $t_1$and the other one at time t_2, where t_1 and t_2 are related such that $t_{CLe,C} < t_1 < t_2 < t_{CLe,Le}$, then the probability of making the simultaneous adoption mistake in the game that begins at t_1 is larger than in the game that starts out at t_2. To understand this result, consider Figure 1: (1) the difference between the payoff from being the first investor and the Leapfrog payoff declines, so that the relative profitability of winning the "investment race" falls, and (2) the difference between the Leapfrog payoff and the payoff that results from simultaneous investment increases so that firms more and more prefer to lose the investment race rather than to make the joint adoption mistake. Furthermore from (18) and the fact that the probability of the joint adoption mistake increases with p, the following ceteris paribus results can be derived: the joint adoption mistake is more likely to occur for lower values of $P(1,0)$, C_e, r, or C_u, and for higher values of C_l, T or $P(1,1)$.

3.4. Equilibrium strategies if learning is negligible and the new technology is expensive

In this subsection solution nr. 2 of Table 1 is analyzed. From the table we obtain that in this case it holds that

$$P(2,1) - C_u - P(1,1) \leq 0, \tag{20}$$

$$P(2,1) - C_l > P(1,1) - C_{d,} \tag{21}$$

$$P(2,2) - C_l \leq P(1,2) - C_d. \tag{22}$$

In Table 1 we see that the cost of upgrading is large in this scenario. This means that, even in case the firm is already active on this market by producing with the current technology, the learning effect is that low that it is still costly to buy and implement the new technology. From (20) it can be concluded that, given that the other firm produces with the current technology, it is not optimal to upgrade so that the Compulsive strategy will not be optimal. The same holds when the other firm produces with the new technology, because then exchanging the current technology for the new one is even less profitable. Taking into account the payoffs of the Leapfrog and the Laggard strategy (cf. (9) and (10)), we can derive from (21) and (22) that the Leapfrog strategy is more profitable than the Laggard strategy if the other firm produces with the current technology, while it is the other way round when the other firm produces with the new technology. Since we already concluded that upgrading is never optimal, it follows that in this scenario demand on the output market is too small for two firms producing with the more expensive new technology.

3.4.1. Exogenous firm roles

Again we first consider the case where one firm is the leader and the other firm the follower. The equilibrium strategies are presented in Figure 2. Since in this scenario the cost

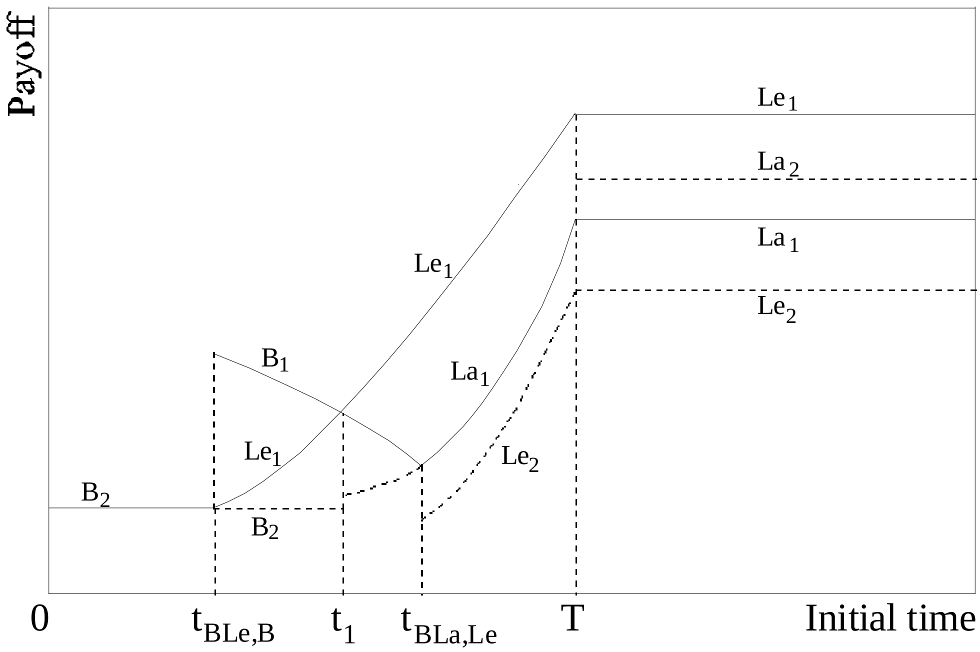

Figure 2. Relevant strategies with their payoffs as function of the initial time of the game, under scenario (20)-(22). B_1 is the Buy and Hold payoff in case the other firm applies Leapfrog, B_2 is the Buy and Hold payoff if both firms apply Buy and Hold, La_1 is the Laggard payoff if the other firm applies Leapfrog, La_2 is the Laggard payoff if both firms apply Laggard, Le_1 is the Leapfrog payoff if the other firm applies Buy and Hold or Laggard, and Le_2 is the Leapfrog payoff if both firms apply Leapfrog.

of upgrading is too high for a replacement of the current technology by the new technology to be profitable, the Compulsive strategy will never be applied. When the point of time T at which the new technology appears on the market is relatively far away, it is optimal for both firms to start producing with the current technology. Therefore, both firms apply the Buy and Hold strategy if the initial time of the game belongs to the interval $[0, t_{BLe,B})$. On the time interval $[t_{BLe,B}, t_{BLa,Le})$ T is not that far away, which implies that, given that the leader follows a Buy and Hold strategy, the follower will prefer Leapfrog. The earnings that arise from producing with the current technology on the time interval before time T are not large enough for the follower to justify the immediate acquisition of the current technology. Note that, given that the leader applies a Buy and Hold strategy, for the follower the Leapfrog payoff is higher than the Laggard payoff (cf. (21)). The fact that the follower plays Leapfrog implies that until the new technology arrives the leader is the only producer on the market. This monopoly position increases revenue before time T, compared to the situation where both firms apply Buy and Hold. On the other hand, after time T the Buy and Hold strategy will generate less revenue, because then the other firm captures a larger share of the market since it produces more efficiently with the new technology. Hence, two contrary effects are working on the Buy and Hold payoff once the follower switches to Leapfrog. Figure 2 is drawn such that the monopoly effect dominates, which explains the upward jump of the Buy and Hold payoff right at $t_{BLe,B}$. But the reverse can also be true. After straightforward calculations it can be concluded that the jump is indeed upward in case it holds that

$$\frac{P(1,1) - C_e}{P(2,1) - C_l} < \frac{P(1,0) - P(1,1)}{P(1,0) - P(1,2)}. \tag{23}$$

We see that in any case at the end of this interval the Buy and Hold payoff is less than the Leapfrog payoff so that the first investor earns less than the follower. Define t_1 as the point of time at which the payoffs of Buy and Hold and Leapfrog are equal (see Figure 2, note that t_1 does not exist in case (23) does not hold). Then, on the interval $[t_1, t_{BLa,Le})$

(or $[t_{BLe,B}, t_{BLa,Le})$ if (23) does not hold) the leader refrains from investment and applies a Leapfrog strategy. The follower is not allowed to invest earlier than the leader, so he has to choose between Leapfrog and Laggard. The follower's choice will be Laggard, since this leaves him with the highest payoff (cf. (22)). On the interval $[t_{BLa,Le}, T)$ the arrival time of the new technology is that close that for both firms it is not optimal to invest immediately. One firm will adopt the new technology as soon as it arrives. The other firm waits until time T to acquire the current technology, since from this time onwards the acquisition cost of the current technology is lower (cf. (3)). Note that, given the fact that one firm plays Leapfrog, expression (22) implies that for the other firm the Laggard strategy is most profitable. The reason is that the demand for output is too low for the two firms to produce both with the new expensive technology. On the last interval $[T, \infty)$ the firms can choose among investing right away in the current and the new technology. One firm will adopt the new technology. Give this choice, it is optimal for the other firm to invest in the current technology at the cheaper price C_d.

3.4.2. Endogenous firm roles

In this subsubsection it is not specified beforehand which firm will be the first investor, so that both firms can be leader or follower. As said before this seems the proper way to analyze a duopoly with identical firms. Since firms are identical, we restrict ourselves to symmetric strategies. From Figure 2 it is obtained that only for the interval $[0, t_{BLe,B})$ the strategies of both firms are identical, implying that the equilibrium for games starting out at a point of time that belongs to this interval is the same for the exogenous and the endogenous firm roles case. To solve the whole problem we divide the remaining time interval into three subintervals and treat the three cases in reversed order of timing. Therefore, we start at the back and thus consider the interval $[T, \infty)$ first.

Game with starting point on the interval $[T, \infty)$ The game we analyze now has an initial point of time $t_0 \geq T$. Since the highest payoff can be obtained by a Leapfrog strategy (provided that the other firm plays Laggard), it is attractive to be the first investor in the new technology (which is available since on this interval the game starts out at a point of time after time T). However, when both firms apply the strategy "invest right away in the new technology at time t_0", with probability one they end up with a payoff $P(2,2) - C_l$, which is less than what could be obtained by investing in the current technology (cf. (22)). Hence, it seems that a mixed strategy is called for. Define $V(t)$ as the value of the firm at time t, $p_1(t)$ is the probability that the firm invests in the new technology at time t, $p_2(t)$ is the probability that the firm invests in the current technology at time t, and $q_1(t)$ and $q_2(t)$ equal the probability that the other firm at time t invests in the new and the current technology, respectively. Furthermore, Le_1 stands for the Leapfrog payoff when the other firm adopts the current technology, Le_2 is the payoff when both firms apply the Leapfrog strategy, La_1 is the Laggard payoff when the other firm plays Leapfrog, and La_2 is the payoff both firms obtain when they both play Laggard. Then the value of the firm is given by

$$\begin{aligned} V = {} & p_1 (1 - q_1 - q_2) Le_1 + p_1 q_2 Le_1 + p_1 q_1 Le_2 + p_2 (1 - q_1 - q_2) La_1 + \\ & p_2 q_2 La_2 + p_2 q_1 La_1 + (1 - p_1 - p_2)(1 - q_1 - q_2) V + \\ & (1 - p_1 - p_2) q_2 Le_1 + (1 - p_1 - p_2) q_1 La_1. \end{aligned} \tag{24}$$

Rewriting gives the expression for the value of the firm for a game starting somewhere within the interval $[T, \infty)$:

$$V = \frac{\left(p_1\left(1-q_1\right)+\left(1-p_1-p_2\right)q_2\right)Le_1+p_1q_1Le_2+}{1-\left(1-p_1-p_2\right)\left(1-q_1-q_2\right)} \\ \frac{\left(p_2\left(1-q_2\right)+\left(1-p_1-p_2\right)q_1\right)La_1+p_2q_2La_2}{1-\left(1-p_1-p_2\right)\left(1-q_1-q_2\right)}. \tag{25}$$

To find the optimal value for p_1 and p_2, differentiate V with respect to p_1 and p_2 and eventually obtain that

$$\begin{aligned} V_{p_1} = & \frac{\left(\left(1-q_1-q_2\right)\left(p_2+q_1-p_2q_1\right)\right)Le_1+}{\left(1-\left(1-p_1-p_2\right)\left(1-q_1-q_2\right)\right)^2} \\ & \frac{\left(\left(1-\left(1-p_2\right)\left(1-q_1-q_2\right)\right)q_1\right)Le_2+}{\left(1-\left(1-p_1-p_2\right)\left(1-q_1-q_2\right)\right)^2} \\ & \frac{\left(-q_1-p_2\left(1-q_2\right)\left(1-q_1-q_2\right)\right)La_1+}{\left(1-\left(1-p_1-p_2\right)\left(1-q_1-q_2\right)\right)^2} \\ & \frac{-p_2q_2\left(1-q_1-q_2\right)La_2}{\left(1-\left(1-p_1-p_2\right)\left(1-q_1-q_2\right)\right)^2} \\ = & \, 0, \end{aligned} \tag{26}$$

$$\begin{aligned} V_{p_2} = & \frac{\left(-q_2-p_1\left(1-q_1\right)\left(1-q_1-q_2\right)\right)Le_1+}{\left(1-\left(1-p_1-p_2\right)\left(1-q_1-q_2\right)\right)^2} \\ & \frac{-p_1q_1\left(1-q_1-q_2\right)Le_2+}{\left(1-\left(1-p_1-p_2\right)\left(1-q_1-q_2\right)\right)^2} \\ & \frac{\left(1-q_1-q_2\right)\left(p_1+q_2-p_1q_2\right)La_1+}{\left(1-\left(1-p_1-p_2\right)\left(1-q_1-q_2\right)\right)^2} \\ & \frac{\left(q_2-q_2\left(1-p_1\right)\left(1-q_1-q_2\right)\right)La_2}{\left(1-\left(1-p_1-p_2\right)\left(1-q_1-q_2\right)\right)^2} \\ = & \, 0. \end{aligned} \tag{27}$$

Using the computer program Mathematica we verified that V is concave in (p_1, p_2), so that satisfying (26) and (27) indeed leads to a maximal value of the firm. Since firms are identical we restrict ourselves to symmetrical strategies which implies that

$$p_1 = q_1, p_2 = q_2. \tag{28}$$

Substitution of (28) into (26) and (27) leads to the following set of equations:

$$\begin{aligned} V_{p_1} =& \frac{(1-p_1-p_2)(p_2+p_1-p_1p_2)Le_1 + (p_1-(1-p_2)(1-p_1-p_2)p_1)Le_2}{\left(1-(1-p_1-p_2)^2\right)^2} \\ & \frac{-(p_1+p_2(1-p_2)(1-p_1-p_2))La_1 - p_2^2(1-p_1-p_2)La_2}{\left(1-(1-p_1-p_2)^2\right)^2} \\ =& 0, \end{aligned} \tag{29}$$

$$\begin{aligned} V_{p_2} =& \frac{-(p_2+p_1(1-p_1)(1-p_1-p_2))Le_1 - p_1^2(1-p_1-p_2)Le_2}{\left(1-(1-p_1-p_2)^2\right)^2} \\ & \frac{+(1-p_1-p_2)(p_1+p_2-p_1p_2)La_1 + (p_2-p_2(1-p_1)(1-p_1-p_2))La_2}{\left(1-(1-p_1-p_2)^2\right)^2} \\ =& 0. \end{aligned} \tag{30}$$

Taking into account that p_1 and p_2 are probabilities so that they have a value not lower than zero and not greater than one, using Mathematica we found a unique solution that satisfies (29) and (30):

$$p_1 = \frac{Le_1 - La_1}{Le_1 - Le_2} = \frac{P(2,1) - C_l - (P(1,2) - C_d)}{P(2,1) - P(2,2)}, p_2 = 0. \tag{31}$$

The important conclusion that can be drawn from (31) is that the optimal mixed strategy does not assign a positive probability to investing in the current technology. The obvious reason is that the highest payoff is obtained when the firm is the first investor in the new technology. The strategy looks very much the same as the one we found in Subsubsection 3.3.2. Also here it holds that one of the firms will surely invest in the new technology right at the start of the game. As soon as this has happened the other firm adopts the current technology. The bad thing that can happen is that both firms invest in the new technology at the same time, leaving them with a low payoff $Le_2 = P(2,2) - C_l$. Analogous to Subsubsection 3.3.2, the probability that this happens equals $p_1/(2-p_1)$, which is increasing in p_1. From (31) it can be obtained that this probability approaches one when Le_2 approaches La_1, thus when the resulting payoff is the same as the one associated with adopting the current technology. Since p_1 is constant over time, the probability of making this mistake does not change as time passes. Substitution of (28) and (31) into (25) gives

$$V = La_1. \tag{32}$$

Hence, the value of the firm resulting from the optimal mixed strategy described by (31) equals the payoff associated with the Laggard strategy.

Game with starting point on the interval $[t_{BLa,Le}, T)$ Figure 2 learns that the optimal strategies are Leapfrog and Laggard, i.e. no investment takes place at this interval. The firms wait until the arrival of the new technology after which the game as described for the interval $[T, \infty)$ will be played. Therefore, the value of the firm is still equal to the Laggard payoff, and from Figure 2 it can be concluded that this value increases when T comes nearer.

Game with starting point on the interval $[t_{BLe,B}, t_{BLa,Le})$ It turns out to be convenient to divide this interval into two: $[t_{BLe,B}, t_1)$ and $[t_1, t_{BLa,Le})$[7]. Let us first consider $[t_{BLe,B}, t_1)$.

[7] Here t_1 is defined such that at this time the Buy and Hold and Leapfrog payoff are equal. Note that $t_1 \in [t_{BLe,B}, t_{BLa,Le})$ only in case (23) holds. If (23) does not hold, then during the whole interval $[t_{BLe,B}, t_{BLa,Le})$ the Buy and Hold payoff falls below the Leapfrog payoff.

Solving this case leads to analogous results as in Subsubsection 3.3.2. In the symmetric equilibrium both firms invest with probability p in the current technology in order to apply a Buy and Hold strategy, where p equals

$$p = \frac{B_1 - Le_1}{B_1 - B_2}. \tag{33}$$

B_1 equals the Buy and Hold payoff when the other firm applies Leapfrog, and B_2 is the payoff if both players perform Buy and Hold. Equation (17) also holds here so that right at the start of the game one of the firms will invest in the current technology. The other firm refrains from investment until time T at which it will adopt the new technology. The probability that both firms invest in the current technology exactly at the same time again equals $p/(2-p)$. It is unclear how p develops over time, since two contrary effects are working here: (1) the difference in payoffs between leading and following decreases over time which has a negative effect on p, and (2) the difference in payoffs between leading and joint adoption decreases as time passes which has a positive effect on p. Finally, we analyze games with their starting point somewhere on the interval $[t_1, t_{BLa,Le})$. Compared to the previous case, here the new technology will become available sooner, which implies that the Leapfrog strategy is more profitable than Buy and Hold. Therefore, the payoff of the first investor is lower than the payoff of the follower, so that a second mover advantage arises. Hence, each firm prefers to be the follower, but if it has to be the first investor, it prefers to invest earlier rather than later, because the Buy and Hold payoff falls over time. Games with this kind of payoff structure are commonly called war of attrition (see Hendricks *et al.* (1988)). A possible strategy would be to "refrain from investment" during this interval, waiting for the other firm to invest. Since with identical firms there is no reason to believe why the other firm would act differently, nothing happens on this interval. Also no investment takes place during the interval $[t_{BLa,Le}, T)$, implying that both firms end up with playing the game on the interval $[T, \infty)$, which is described above. The expected value of the firm obtained from playing this game equals the Laggard payoff, and in Figure 2 we see that this payoff lies below Buy and Hold and Leapfrog. In Hendricks *et al.* (1988) the subgame perfect equilibrium is given for the war of attrition with identical firms, as it occurs here. Define $G(t)$ as a probability distribution on $[t_0, t_{BLa,Le})$, where $t_0 \geq t_1$ is the starting point of the game. In fact, $G(t)$ equals the probability that the firm has invested in the current technology at or before t. According to Hendricks *et al.* (1988) a mixed investment strategy described by

$$G(t) = 1 - \exp\left(\int_{t_0}^{t} \frac{\frac{dB_1(s)}{ds}}{Le_1(s) - B_1(s)} ds\right), \tag{34}$$

and performed by both firms, is a subgame perfect equilibrium. Hendricks *et al.* (1988) show that any mass point can be ruled out implying that the probability that a firm moves exactly at a particular point of time equals zero[8]. Consequently, the probability that the two firms move exactly at the same time is also zero, which explains why B_2 (thus the payoff in case both firms play Buy and Hold) does not affect the mixed investment strategy in (34). From (34) it is easily obtained that $G(t_{BLa,Le}^{-}) < 1$. Note that, if this were not the case, the symmetric investment strategy is not a Nash equilibrium. The reason is that when $G(t_{BLa,Le}^{-}) = 1$, then one of the firms could do better by refraining from investment during

[8] The implication is that, in the notation of previously described games, e.g. like the one starting at the interval $[t_{BLe,B}, t_1)$, $p(t)$ equals zero for all relevant t.

the interval $[t_0, t_{BLa,Le})$, since this firm knows for sure that its competitor will have invested at some time before $t_{BLa,Le}$. Substitution of the relevant formulas for the payoffs, given in Subsection 3.1, into (34) leads to

$$G(t) = 1 - \exp\left(\int_{t_0}^{t} \frac{re^{-r(T-s)}\left(P\left(1,2\right) - P\left(1,0\right)\right)}{C_e - P\left(1,0\right) + e^{-r(T-s)}\left(P\left(2,1\right) - C_l - P\left(1,2\right) + P\left(1,0\right)\right)} ds\right). \quad (35)$$

The firm's willingness to invest increases with the relative performance of Buy and Hold compared to Leapfrog. In this light the following ceteris paribus results, that are derived from (35), are easy to understand: G goes up with r, T, $P(1,0)$, C_l, and goes down with C_e, $P(2,1)$ and t_0.

4. Conclusions

This paper treats the technology adoption decision of the firm in a duopoly framework. One of the main difficulties concerning the technology investment decision in practice is that in the future better technologies than now available will be invented. The model in this paper tries to capture this important aspect by considering two technologies: one which is available now, and the other one which is more efficient and becomes available at a known point of time in the future. By doing so, work of Reinganum (1981), Fudenberg and Tirole (1985), Hendricks (1992), and Stenbacka and Tombak (1994), who consider only one technology, is extended. Moreover, learning is incorporated in the way that adoption of the current technology makes it less costly to adopt and implement the new technology. We focussed on the scenario where for every technology investment it holds that the discounted future profit stream exceeds the immediate expenditure. In case the arrival date of the new technology lies far in the future, the future presence of a new technology does not prevent that investing in the current technology is still optimal. When this date comes nearer it is not optimal anymore for both firms to invest in the current technology right away. Hence, one of the firms has to refrain from investment, which implies that by investing in the current technology the other firm obtains monopoly profits until the arrival date of the new technology. To capture these monopoly profits a firm must try to invest earlier than its competitor. In this way the preemption equilibria arise that we already know from, e.g., Fudenberg and Tirole (1985), but here no rent equalization occurs as was the case in that paper. A consequence of the absence of rent equalization is that a positive probability arises that both firms invest at the same time, leaving them with a very low payoff (in Fudenberg and Tirole (1985) the probability of occurrence of this "mistake" was zero due to rent equalization). Another new element in our paper is the occurrence of second mover advantages in technology adoption problems. This happens in scenarios where technology upgrading is not optimal so that firms have to make a choice between investing in the current technology right away and keep on producing with it, or waiting with investment until the new technology arrives. The advantage of the immediate investor is that monopoly profits are gained until the arrival of the new technology, while the investor in the new technology has the advantage of producing with a better technology once it is available. A second mover advantage arises when the advantage of producing with the new technology in the future leads to a higher payoff than the current temporary monopoly profits. An immediate extension of the model in this paper is to add uncertainty. A distinction can be made between uncertainty concerning the arrival date of new technologies or uncertainty concerning the efficiency of new technologies.

For instance, in case of microchips the technical parameters and specifications of future designs are known beforehand, but the arrival date is uncertain since the appearance of the technology depends on research and development and the market factors affecting the introduction of the product (Nair (1995)). Another interesting topic of future research is to incorporate asymmetric information in the sense that a firm does not know how profitable a particular innovation is for its opponent. However, as time passes the firm learns about the other firm's profit function from the observed investment behavior of the other firm. Based on this observation it will update its conjecture about the other firm's profit function.

References

Dutta, P. K., S. Lach and A. Rustichini (1995). Better late than early: Vertical differentiation in the adoption of a new technology. *Journal of Economics and Management Strategy*, **4**, 563–589.

Fudenberg, D. and J. Tirole (1985). Preemption and rent equalization in the adoption of new technology. *Review of Economic Studies*, **52**, 383–401.

Grenadier, S. R. (1996). The strategic exercise of options: Development cascades and overbuilding in real estate markets. *Journal of Finance*, **51**, 1653–1679.

Grenadier, S. R. and A. M. Weiss (1997). Investment in technological innovations: An option pricing approach. *Journal of Financial Economics*, **44**, 397–416.

Hendricks, K. (1992). Reputations in the adoption of a new technology. *International Journal of Industrial Organization*, **10**, 663–677.

Hendricks, K., A. Weiss and C. Wilson (1988). The war of attrition in continuous time with complete information. *International Economic Review*, **29**, 663–680.

Nair, S. K. (1995). Modeling strategic investment decisions under sequential technological change. *Management Science*, **41**, 282–297.

Reinganum, J. F. (1981). On the diffusion of new technology: A game theoretic approach. *Review of Economic Studies*, **48**, 395–405.

Simon, L. K. (1987). A multistage duel in continuous time. Working Paper 8757, Department of Economics, University of California Berkeley, Berkeley, California.

Stenbacka, R. and M. M. Tombak (1994). Strategic timing of adoption of new technologies under uncertainty. *International Journal of Industrial Organization*, **12**, 387–411.

Yorukoglu, M. (1998). The information technology productivity paradox. *Review of Economic Dynamics*, **1**, 551–592.